Environmental Engineering Grade A Shock Tests

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***Abstract*- This paper can help provide better insight to the rationale behind one of the important and critical destructive tests: the Environmental Shock Test. One may ask, why build a highly functional working model or system and then subject it to severe harsh blows? Today's Navy and other military branches are relying more heavily on Commercial-Off-The-Shelf (COTS) hardware. It has been a challenge to all managers, engineers and administrators to operate under limited budget and reduced resources. In some cases, one may even take the option of dangerous steps of short cuts and cost cutting technique such as unjustified exemptions. This paper can serve as a challenge to managers, developers, and systems integrators not only in the government but also in the industry. It may provide some insight and understanding of the ways we do business in the environmental engineering areas in order to provide and deliver a system that can withstand harsh environment as well as maintain fighting capability during combat.**

I. INTRODUCTION

Limited budget, reduced resource allocations, and cost cutting have posed significant challenges to project managers and program administrators. In the past, basic design engineers, system engineers, system integrators, managers, and project leaders have followed solely the military specifications and standards to build equipment for the military environment. With the availability of the vast leading edge technologies in the commercial world coupled with reduced resources, the military systems have adopted and expanded usage of Commercial Off-The-Shelf (COTS) components. Despite these challenges, preservation of the fundamental and essential safety of military personnel and the combat capability of the Navy's fighting ships are still crucial. Combat survivability of instrumentation is significant on the battlefield. Fighting ships have to carry out their mission in extreme conditions, which often include exposure to such hazards as fire, electromagnetic interference and shock. These are the reasons why established policies, guidelines and essential requirements play significant roles in ship, equipment, systems design and acquisition. Widespread use of COTS poses challenges to survivability. The only way we can ensure that the use of latest technology and new products offered by industry supports the combat capability and survivability of our fighting ships is to maintain the Grade A shock testing. This is the only way we can reduce vulnerability and prevent catastrophic loss of critical functions.

II. SHOCK TEST REQUIREMENT – BASIC TUTORIAL

Survivability is the capacity of the ship to absorb damage and maintain mission integrity. Warships are expected to perform offensive missions, to sustain battle damage and to survive. As such, ships personnel on board must be sufficiently trained and ships equipment must be sufficiently hardened to withstand various threat levels.

To attain this minimum baseline of survivability, installed equipment hardened to appropriate standards must be implemented through appropriate ship and equipment specifications. A shock testing requirement verifies the ability of installations to withstand shock loadings, which may be incurred during wartime service due to the effects of nuclear or conventional weapons [1].

Specification requirements are driven by the equipment application. The selection of a suitable standard or specification for a specific design application is the responsibility of the procuring activity.

There are required levels of shock resistance of shipboard equipment and systems and are classified into two grades, Grade A and Grade B. These Grades are defined as follows [1,2]:

Grade A: Grade A systems, subsystems, or items are those which are considered by Naval Sea Systems Command (NAVSEA) to be essential for the safety and continued combat capability of the ship. These equipment and systems are propulsion, ship control, navigation, command, control and communication, surface, air and underwater surveillance, countermeasures, fire control, firing or launching, guidance of weapons, interior communication and data processing systems needed to support the essential mission. Ship has to retain these general capabilities during and after attack without significant impairment of the systems.

In the previous wars, the loss of HMS Sheffield in 1982 and the crippling of USS Stark in 1987 highlighted the vulnerabilities of surface warships not adequately equipped or prepared to counter the modern Anti-Ship Cruise Missiles (ASCMs) approaching under the radar horizon [3].

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **01 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Environmental Engineering Grade A Shock Tests**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **SPAWAR Systems Center San Diego 53560 Hull Street San Diego, California, 92152-5001, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002146. Oceans 2003 MTS/IEEE Conference, held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Part of the problems was also attributed to shock and Electromagnetic Interference (EMI).

Grade B: Grade B systems are items whose operation is not essential to the safety and combat capability of the ship but which could become a hazard to personnel, to Grade A equipment, or to the ship as a whole as a result of exposure to shock.

Shock testing validates shock resistance of mission-essential items, and validation of total ship hardness including onboard mission-essential items (installed and /or stowed configurations). This is accomplished by ship shock trials [4].

Items to be tested are also classified into three classes: Class I, Class II, and Class III. Class I equipment is defined as that which is required to meet these shock requirements without the use of resilient mountings installed between the equipment and the ship structure or foundation. Class II equipment is defined as that which is required to meet these shock requirements with the use of resilient mountings installed between the equipment and the ship structure or shipboard foundation. Class III equipment is defined as that which has shipboard application both with and without the use of resilient mountings and is therefore required to meet both Class I and Class II requirements.

III. GRADE A SHOCK – BASIC THEORY, METHOD AND PRACTICE

As one may recall in his or her early years of engineering classes, the law of physics holds true to either electrical or mechanical world. The response of the basic Resistive-Inductive-Capacitive (RLC) electrical circuit and a simple mass-spring-viscous damper, as shown in Fig. 1, to a forcing function may be expressed in a similar mathematical model. Each model does exhibit the *damped natural frequency* of the system.

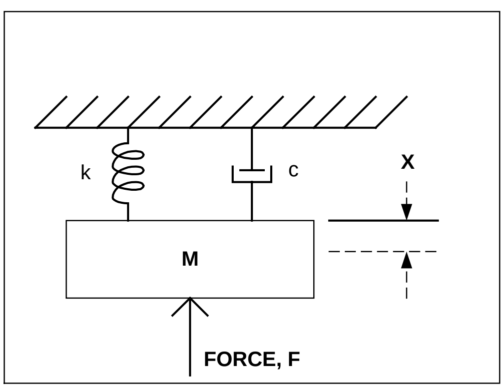

Fig. 1. A single-degree-of-freedom system with viscous damping and excitation force, F

Fig. 1. is a single degree-of-freedom system with viscous damping and subjected to a varying excitation force F= F(t). The differential equation of motion for this system is Equation (1.1) [5,6]:

$$md^2x/dt^2 + cdx/dt + kx = F(t) \tag{1.1}$$

or

$$d^2x/dt^2 + (c/m)dx/dt + (k/m)x = F(t)/m \tag{1.2}$$

where:

x = displacement coordinate; displacement of the system as a function of time
dx/dt = velocity of the mass
d^2x/dt^2 = acceleration
$(c)dx/dt$ = damping force
c = damping coefficient
m = mass
k = spring constant
$F(t)$ = External forcing function

As we may recognize, (1.2) represents a second-order, ordinary differential equation of the type most commonly encountered in elementary vibration or in shock analysis. To obtain the complete solution of the differential equation, we must determine both a particular solution *(Xp)* which satisfies (1.2) and the homogeneous solution *(Xh)*, which also satisfies (1.2.), i.e.

$$d^2/dt^2\,(Xp) + (c/m)d/dt\,(Xp) + (k/m)Xp = F(t)/m \tag{1.3}$$

$$d^2/dt^2\,(Xh) + (c/m)d/dt\,(Xh) + (k/m)Xh = 0 \tag{1.4}$$

The complete solution to the differential equation is the sum of (1.3) and (1.4):

$$d^2/dt^2\,(Xp) + (c/m)d/dt\,(Xp) + (k/m)Xp + d^2/dt^2\,(Xh) + (c/m)d/dt\,(Xh) + (k/m)Xh = F(t)/m + 0 \tag{1.5}$$

or by collecting terms in the equation, we get

$$d^2/dt^2(Xp + Xh) + (c/m)d/dt(Xp + Xh) + (k/m)(Xp + Xh) = F(t)/m \tag{1.6}$$

Eq. 1.1 is the typical equation of motion for the mass m of the passive control system. If a step function is chosen as the forcing function $F(t)$ with a magnitude $F = Fo$ when $t > 0$ and $F = 0$ when $t < 0$, we can find the typical time solution by taking the Laplace transform of the equation:

$$\mathcal{L}\,[x(t)] = X(s) = (Fo/ms)\{1/[s^2 + (c/m)s + k/m]\} \tag{1.7}$$

Where $X(s)$ is the Laplace transform of x, a function of time. The initial condition $x(0^+)=0$ and $d/dt[x(0^+)]=0$.

For a conventional control system, the transmissibility T of a system at the condition of resonance is [5]:

$$T = (1/c)(km)^{1/2} = 1/[2(c/c_c)] \qquad (1.8)$$

Where:

c = damping coefficient
c_c = critical damping coefficient
c/c_c = damping ratio< 0.2
m = mass
k = spring constant

Similarly, the resonance frequency Wr is approximately equal to the undamped natural frequency ω_n [5]:

$$\omega_n = (k/m)^{1/2} \qquad (1.9)$$

or

$$(\omega_n)^2 = k/m \qquad (1.10)$$

From (1.8) and (1.10), we can derive the relationship:

$$2\,(c/c_c)\omega_n = c/m \qquad (1.11)$$

Using (1.10) and (1.11), equation (1.7) may be written as:

$$X(s) = (Fo/ms)\{1/\,[s^2 + 2(c/c_c)\omega_n s + \omega_n{}^2]\,\} \qquad (1.12)$$

The typical time solution of (1.12) is a damped sinusoid. Example of the waveform is shown in Fig. 2.

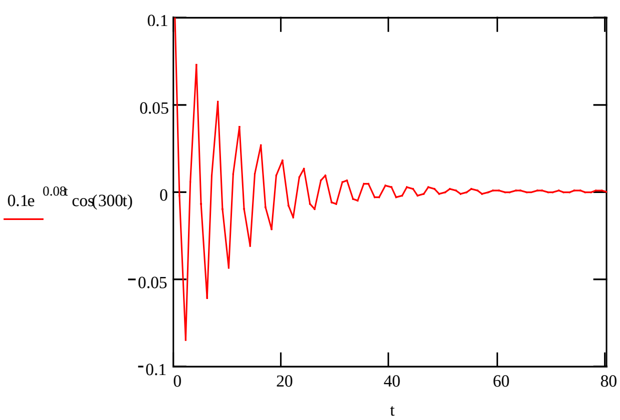

Fig. 2. Damped sinusoid waveform. Example of a typical time solution for a system with step function as the forcing function

We can then apply the final value theorem to determine the movement of the isolator coil represented by k and c in Fig. 1.

$$\lim_{s\to 0} sX(s) = \lim_{t\to\infty} x(t)$$

$$\lim s\,(F_0/ms)\,\{1/[s^2 + 2(c/c_c)\omega_n s + (\omega_n)^2\} = (F_0/m)(1/\omega_n{}^2) \qquad (1.13)$$

The discussion above is a description of a basic method of finding solution for a simple system. The solution in (1.6) gives the displacement x of the mass from the reference position as a function of time. The magnitude of that displacement is the actual response of the system to the shock, which can be expressed as the time-history of a parameter that describes the motion of the system.

For this system, the magnitudes of the response peaks can be summarized as a function of the natural period of the responding system (natural frequency), at various values of the fraction of critical damping [5].

Forcing functions are shock motions that may be selected for analysis and can be captured for data reduction. Examples of shock motions are the delta (impulse) function, unit step function, half-sine acceleration, decaying functions and complex shock motion. All of these can be defined mathematically except for the complex shock motion. In reality, forcing functions may be a complex shock motion with an unknown functional form and cannot be defined by analytic function. Therefore it is determined by actual measurement. Typical example of a complex shock motion is shown in Fig. 3.

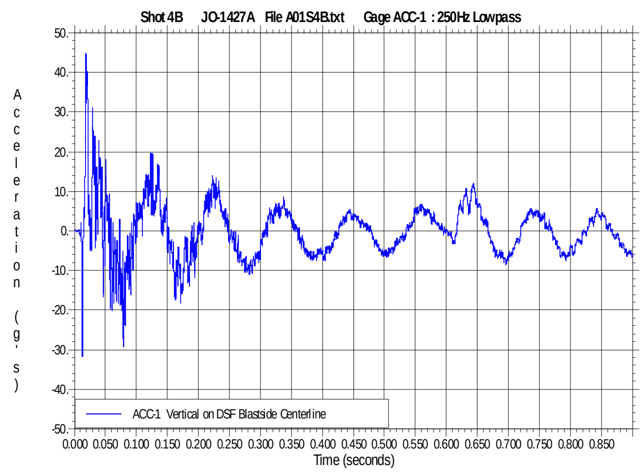

Fig.3. Typical example of a complex shock motion. This sample is the result of actual measurement

It is a common practice to prove the design of equipment by actual shock tests that simulate the anticipated operational shock condition. This is a realistic approach and an alternative option to the difficulties of using analytical methods in the design of equipment to withstand severe shock.

An actual system may consist of hundreds or thousands of vital components that need to be qualified as Grade A. Going through the analytical process for each one of these components may be a tedious process especially if the system has multiple degrees-of -freedom.

Fig.4 is the typical configuration and commonly used structural model of the heavyweight shock test. It consists of two basic structures, primary and secondary structure. The Floating Shock Platform (FSP) supports the primary and secondary structures and the Deck Simulator Fixture

(DSF) supports the secondary structure. The secondary mass m is much smaller than the primary mass M. The response of the primary mass to an input shock motion is the input shock motion to the secondary structure.

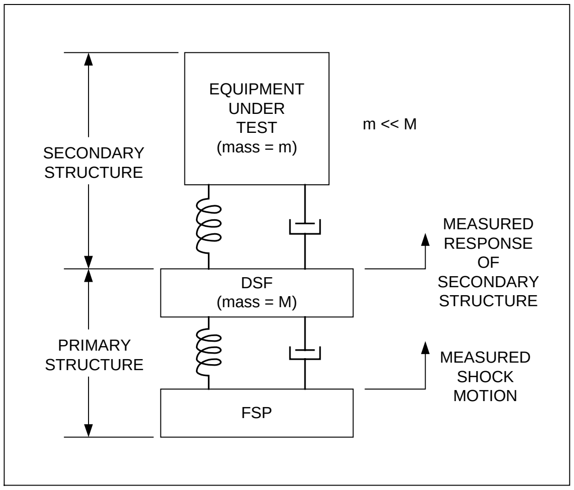

Fig. 4. Normal configuration and structural model of a primary and a secondary structure used in barge testing.

IV. A CASE OF GRADE A SHOCK – REAL SHOCK AND LESSONS LEARNED

Fig. 5. shows the model of the setup of the Heavyweight High Impact Shock Testing (Barge Test) of the Navigation Sensor System Interface (NAVSSI) Display Control Subsystem (DCS) system.

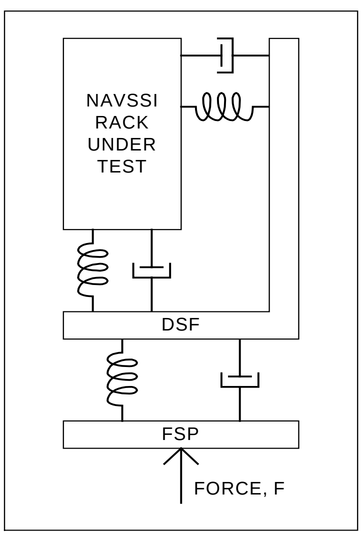

Fig. 5. Structural model and setup of the Heavyweight High Impact Shock Testing of the Navigation Sensor System Interface (NAVSSI) system

A. *Test Process and Preparation*

All test fixtures should dynamically simulate the most severe mounting condition likely to be encountered onboard ship. Standard fixtures are to be used whenever possible and all special fixtures must be approved by NAVSEA 05P3 or NSWCCD code 623 as per NAVSEAINST 9072.1A. Heavyweight shock tests require a test procedure and test fixture drawing which must also be approved by the NAVSEA 05P3/NSWCCD Code 623.

Fig. 6 shows the picture of the equipment rack under test installed on the DSF and the DSF was mounted on a FSP whose inner bottom provides overall support to the primary and secondary structures. Accelerometers were installed on the DSF and FSP to verify proper test geometries and to monitor shock input parameters and response frequencies. The rack system design calls for using base shock isolators and rear stabilizing isolators.

Fig. 6. Pictorial view of the NAVSSI rack under test. The rack was installed in a Floating Shock Platform (FSP) on Deck Simulator fixture

Extensive preparations are necessary prior to shock testing. See Fig. 7. A thorough visual examination of the test item has to be performed to locate any of the following:

- Broken, loose or deformed parts
- Cracked welds
- Other evidence of physical damage
- Any condition that could endanger equipment or personnel during subsequent testing

Physical inspections, built in tests, and functional tests have to be conducted to ensure that no discrepancies were observed prior to shots. This practice also applies following each shot to assess the results.

Fig. 7. NAVSSI DCS installed on the Barge for Grade A Shock Test

Two test sequences were conducted against the NAVSSI DCS rack. On the first four shots, the DSF, with the equipment installed, was tuned to provide a fundamental vertical response frequency of 14 +/-2 Hz. These are the qualification shots for the general class ships such as CG, DDG and LPD. On the last two shots, the DSF was tuned to 10 +/-1 Hz. These are the qualification shots for the carrier type decks (CVs / CVNs). A picture of one of the test shots is shown in Fig 8.

The six test shots used the standard sixty-pound Navy explosive charges that were suspended twenty-four feet beneath the water surface at horizontal standoff of 30,25 and 20 feet from the near side of the FSP. Shots were conducted in the order listed in Table 1.

Table 1. Test Geometries for NAVSSI DCS shock test

TEST GEOMETRIES FOR NAVSSI DCS SHOCK TEST (14 +/-2 HZ AND 10 +/- 1 HZ DSF)				
Shot No.	Charge Depth (ft)	Horizontal Standoff (ft)	Location of Charge with Respect to the FSP	Orientation of Test Item Front-to-Back Axis with Respect to Fore/Aft Axis of FSP
2	24	30	Athwartship	Parallel
3	24	25	Athwartship	Parallel
4	24	20	Athwartship	Parallel
4R	24	20	Athwartship	Perpendicular
4RA	24	20	Athwartship	Parallel
4RB	24	20	Athwartship	Perpendicular

Grade A items had to be tested while in their normal operating modes, positions, and conditions. Operational tests were conducted on the NAVSSI DCS to insure that the requirements for operation were being met before, during, and after each shot of the test series. Using the installed instrumentation inside the rack, the performance of the system was monitored to insure normal operation before, during and after each shot.

For this shock test series, the deck fixture frequency was defined as the frequency associated with the peak magnitude value of the Fast Fourier Transform (FFT) of the raw data from accelerometer installed in the DSF centerline [7].

Fig. 8. A Barge Test shot at HI-TEST Laboratories, Inc.

B. *Test Results*

The NAVSSI DCS rack continued to operate normally and no damage was observed following each of four shots of the first test sequence. This qualified it for the 14 Hz platforms, CGs, DDGs, and LPDs.

The second test sequence was conducted with the rack installed on a 10 +/- 1 Hz DSF (for Carrier installation). This test sequence consisted of two 20 ft standoff athwartship shots, designated shots 4RA and 4RB, with the front of the rack facing athwartship. Testing was terminated following shot 4RB due to the following failures which violated Grade A and Grade B shock test acceptance criteria:

- The hard disk drive and the RAID drive assembly had completely ejected and were found on the deck. This is shown in Fig. 9.

- The keyboard came out and impacted the Flat Panel display, -cracking the front and back glass in the display. This is shown in Fig. 10.

Investigations were made and a closer examination and comparison of the shock input frequency at the DSF and the shock response frequency of the NAVSSI DCS have indicated that the mechanical configuration of the system has reached the resonance frequency. Each location has the same frequency reading of 9.77 Hz.

Fig. 9 DCS RAID Drive assembly missing and out of the rack. Pieces of the raid drives were found on the FSP deck.

Fig. 10. Keyboard hanging from the broken slider.

Fig. 11 and Fig. 12 show the peak magnitude values of the Fast Fourier Transform (FFT) of the accelerometers installed inside the NAVSSI DCS and at the DSF. These figures have clearly revealed that our system as designed resonates on a 10-Hertz deck. This dangerous situation would not have been discovered without shock testing.

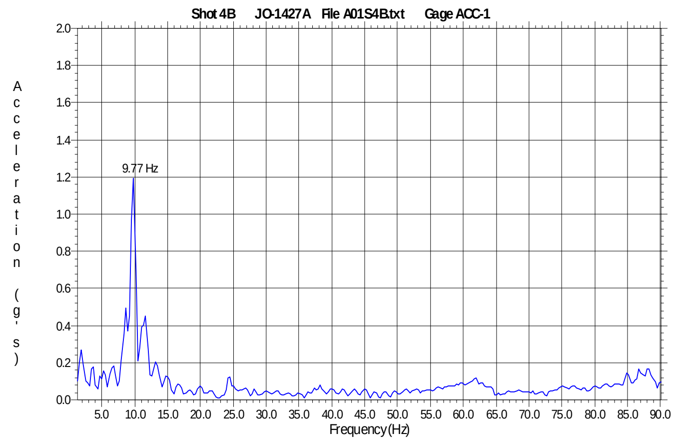

Fig. 11. Frequency response of Deck Simulator Fixture (DSF)

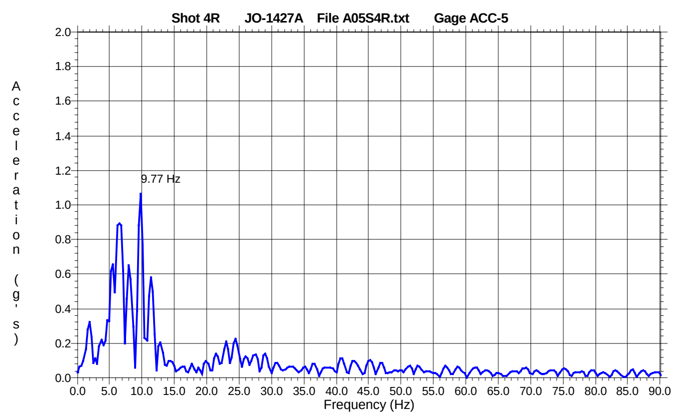

Fig. 12. Frequency response of NAVSSI DCS

Due to the damage and failure of the NAVSSI DCS, repairs and modifications to the system had to be done before the repeat of the 10 Hz shock qualification test.

Careful analysis was done to determine the root cause of the problem and to find the solution to this resonance condition. We looked at the isolation system and an effort was done to develop an isolator coil that would provide adequate isolation for our NAVSSI rack on the 10 Hz FSP. Due to the complex nature of the problem, the selection of the proper coil would involve iteration process in order to determine the best possible solution. Factors such as equipment rigidity, coil stiffness, drop conditions, coupling, factor of safety and height restrictions were considered to minimize the “bottoming out” of the system during shock testing. Predictions were made using models developed in a systems dynamics simulation environment of Finite Element Analysis (FEA) software. Prototypes were built and load-deflection tested. The result was a bigger coil with a natural frequency of 5 to 6 Hertz.

A repeat of the test was done at HI-TEST Laboratories, Inc. with these new isolator coils. The

NAVSSI DCS system went through the required Grade A shock test with no physical or operational discrepancies.

Shock tests fall under one of the following categories: lightweight , mediumweight and heavyweight tests. The lightweight test is a test performed on the lightweight shock machine. In this test, the total weight supported by the lightweight shock machine anvil plate cannot exceed 550 pounds. The mediumweight test is a test performed on the medium weight shock machine. The total weight supported by the medium weight shock machine anvil table cannot exceed 7,400 pounds. The heavyweight test, discussed in this paper, is a test performed on a standard or large floating shock platform.

Shock qualification requires one or more of the following: shock analysis, shock test, and shock extension. A shock qualification analysis requires the equipment to be analyzed in accordance with NAVSEA 0908-LP-00-3010 (DDAM). A shock qualification by test requires the equipment to be tested as detailed in MIL-S-901D and a shock qualification by extension requires the equipment to be extended from a previously shock qualified equipment in accordance with MIL-S-901D or NAVSEA 0908-LP-00-3010 (DDAM) [8].

High Impact Shock Testing may be done on a lightweight shock machine, mediumweight shock machine and heavyweight barge testing using the floating shock platforms, submarine Shock Test Vehicle (SSTV), Full Scale Sections (FSS) and Paddlewheel Test Vehicle (PWTV) [8].

Submarine Shock Tests and Surface Ship Shock Trials are ship trials performed on the lead ship of a new class of submarines or surface ships. The purpose of ship trial is to provide Navy planners and administrators an insight into platform vulnerabilities to underwater bursts. This test may provide significant decision-making data for corrective actions. In a shock test trial, the vehicle is subjected to a series of underwater explosion (UNDEX) shocks generated by large explosive charges at a standoff distances off the bream of a ship. This blast simulates underwater explosions. Ship Shock Trials are performed with a crew on board, and are not intended to damage equipment. A photograph of a surface ship shock trial is shown in Fig. 13.

Fig. 13. USS Winston Churchill (DDG-81) Shock Trial

V. CONCLUSIONS

The abundance and the readily available technologies, new products and services from the commercial industry, combined with limited budget have accelerated the integration of COTS items into shipboard environments. This action increases our uncertainties in the systems that we are designing for our combat ships. One of the options we need to take is to subject our newly designed system to the proper validation tests.

There will always be inherent limitations on everything we do. In the world of environmental testing, decision-making data are usually generated through some combination of testing and computer simulation. Systems can be designed in a way that will allow them to operate in a harsh environment. This may be achieved by careful design followed by extensive analysis and validation testing to provide the right confidence level that our war fighters will succeed and win.

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